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The Effect of Matrix Microstructure on the Abrasion Resistance of High-Cr White Cast Irons

by

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Abstract

The abrasion resistance of high-chromium white cast iron was investigated as a function of cast iron microstructure. Different microstructures were obtained by means of heat treatment. The chromium and carbon contents were chosen in order to have different matrix microstructures (austenitic, martensitic and ferritic) with a content of 30% volume fraction of eutectic carbide (M_7C_3). The abrasion tests were made by using a pin-shaped sample in contact with an abrasive paper having a speed of 3.2 m/min. The two-body abrasion tests were carried out with a constant distance traveled on abrasive paper of 6 m under loads from 26.7 to 80 N. The wear was measured by means of mass loss. The results show that the cast iron with an austenite matrix has the best wear resistance. The good wear resistance of this material is due to strong work hardening of the austenite matrix resulting in a hardness which exceeds that of other structures. Moreover, the deterioration of the eutectic carbides under the worn surface is more pronounced for the soft ferritic cast iron than for the martensitic or austenitic cast irons.

THE USE OF WHITE CAST IRON is often encountered in the mining industry where ore has to be ground (crushers, ball mills) or transported (slurry pumps, liner plates) [1-3]. The addition of chromium leads to the formation of eutectic carbide (M_7C_3) which gives good abrasion resistance because of its high hardness. Moreover, the presence of chromium in the matrix, even in a small amount, imparts good corrosion resistance. The hardness of the eutectic carbides is higher than that of quartz which is present in large proportion in many ore types. This advantage can be considered in the choice of material employed for the fabrication of balls used in ball mills. Because of the level of impact in ball mills, there is always a compromise between good abrasion resistance (hard material) and good impact resistance (tough material).

The wear resistance is not an intrinsic property of materials, rather it depends on a set of conditions defining a system [4]. The bulk hardness of white cast irons is increased when the amount of carbide, the matrix hardness or both are increased [5]. Some studies show that the wear resistance in three-body abrasion [6] and erosion at glancing angles [7] correlates well with the bulk hardness. The interpretation is more difficult when an abrasive harder than the eutectic carbides is used [5]. The different mechanisms involved in two-body and three-body abrasion lead to a different behavior with white cast iron [8]. The wear mechanisms occurring for the eutectic carbides and the matrix are different and strongly related to experimental conditions. For instance, some studies [8,9,10] show that under garnet paper abrasion, white cast iron having a martensite matrix has better wear resistance than white cast iron with an austenite matrix, while the inverse is the case for alumina or silicon carbide abrasive papers. Pearce [11] mentions that experimental or service conditions can be such that work hardening of an austenite matrix is not sufficient to protect the cast iron against abrasion; then martensitic cast irons have better wear resistance in these cases. The severity of abrasion testing is strongly related to the toughness of abrasive particles or the quality of abrasive paper [12]. This again reinforces the idea of a wear system.

The purpose of our study is to investigate the role of the matrix microstructure under severe abrasion. The cast irons to be characterized have the same carbide volume

fraction with different matrix microstructures. These specimens were taken from balls used in a ball mill where the abrasion and impact conditions are intense. In this study, only abrasive wear will be covered.

EXPERIMENTAL PROCEDURES

The high-chromium white-cast-iron balls were supplied by Magotteaux Canada. The compositions and heat treatments were selected so as to obtain different matrix microstructures but with the same carbide volume fraction of nearly 30%. The carbide volume fraction was determined by using Maratray's formula [13]. For the compositions studied, dendritic austenite forms first during cooling and subsequently the eutectic reaction gives M_7C_3-type carbides. The microstructures and the hardness of the white-cast-iron balls are given in Table 1. Cast irons 1A and 3B have a martensite matrix containing eutectic carbides and small secondary carbides (Fig. 1) formed by solid state diffusion during the cooling.

Table 1

Designation	Matrix Structure	HRC	H_S
1A	Martensitic + secondary carbides	62	982
2A	Austenitic	47	1083
3B	Martensitic + secondary carbides	66,5	920
4B	Ferritic - pearlitic + secondary carbides	32	469

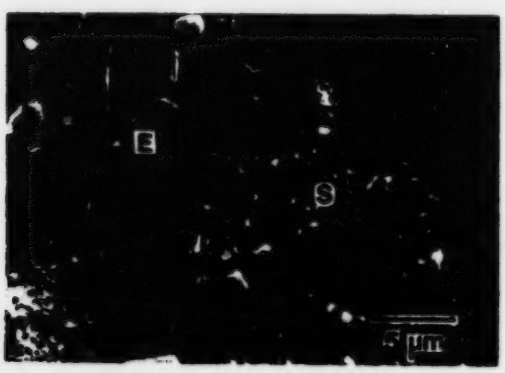


Fig. 1 - Small secondary carbides (S) in the matrix of martensitic cast iron 1A (E: Eutectic carbide). Etched with 4% nital.

One should note that the hardness is constant all along the diameter of the ball. This suggests that the microstructure is nearly the same through the ball. Cast iron 4B has a ferrite matrix obtained by austenizing and quenching at a temperature permitting ferritic transformation. A small amount of pearlite is also observed. Samples 2A with austenitic microstructure were obtained from the same balls as samples 1A. Austenization at 1175°C for two hours results in secondary carbide dissolution in the austenite matrix. The increase in carbon content of the matrix has the effect of decreasing M_S below room temperature. Rapid quenching to room temperature following the austenization results in an austenitic structure. Due to the heat treatment, the eutectic carbides have a more globular form than those of other cast irons. As a consequence of its heat treatment, cast iron 2A contains no secondary carbides. Some samples were cut perpendicularly to the worn surface and etched with a solution made of 5 g of picric acid, 5 ml of hydrochloric acid and 100 ml of ethyl alcohol. The microstructures of each cast iron are shown in Figure 2.

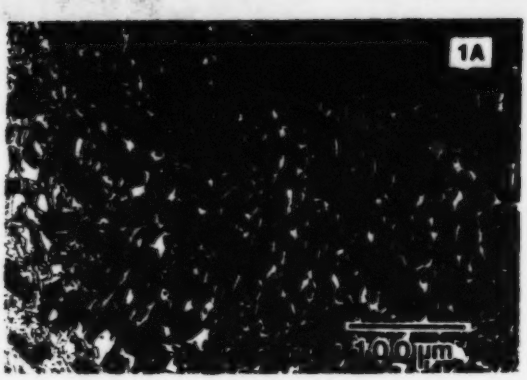
The pin-shaped samples were cut by electro-erosion from balls of 38.1 mm diameter in the as-received condition. Subsequent machining of the pins resulted in samples with final dimensions of 6.35 mm diameter and 25.4 mm length. One end of each pin was ground perpendicular to the longitudinal axis in order to maintain the apparent surface constant during abrasion testing. This surface was polished by using 600 grit SiC paper. Before and after each abrasion test, the samples were cleaned in an ultrasonic bath, dried in hot air and weighed. The wear was measured by means of mass loss.

The two-body abrasion tests were made on an abrasive paper belt. The experimental conditions were set as follows:

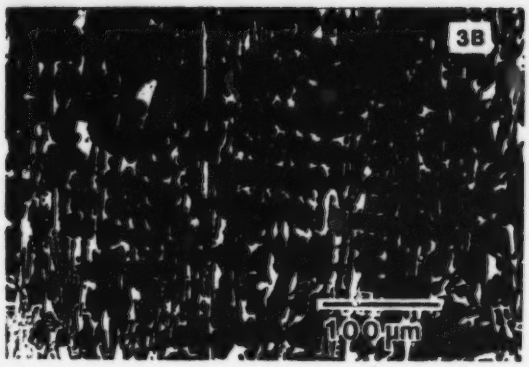
- abrasive paper speed: 3.2 m/min
- sample rotational speed: 20 rpm
- abrasion distance: 6 m
- loads: 26.7, 53.3 and 80.0 N
- abrasive 100 grit (150 µm): garnet, alumina and silicon carbide.

The machine employed permitted lateral displacement in order to garantee that the sample always traveled on virgin paper. A correction factor was introduced in order to take into account the abrasivity variations from one paper belt to another of the same type. The experimental mass loss is then reported as a corrected mass loss.

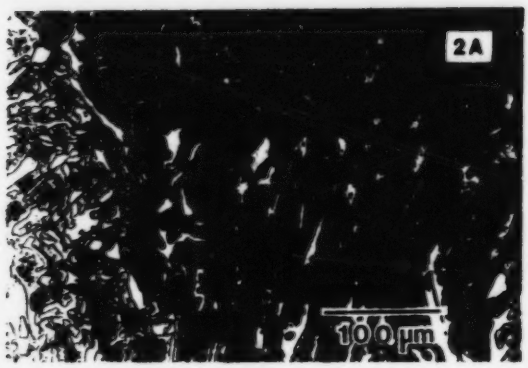
Some microhardness measurements of the matrix were made after the test to determine if structural modifications had occurred. The worn surfaces were lightly polished with 600 grit SiC paper in order to obtain flat surfaces without destroying the deformed layer related to wear. The polishing scratches were much smaller than the ones due to wear. A light etching with 4% nital revealed the



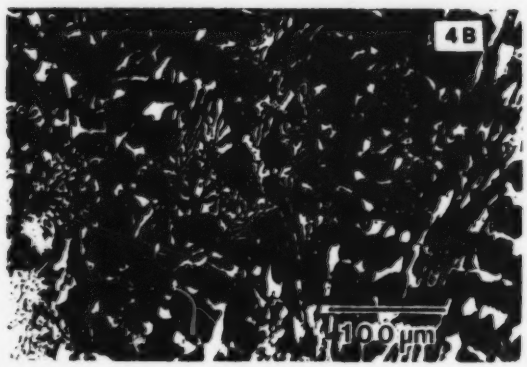
2-a



2-c



2-b



2-d

Fig.2 - Optical micrographs of cast iron structures. a) 1A, b) 2A, c) 3B and d) 4B.

carbide and matrix phases. The microhardness measurements were made between the carbides and the penetration marks were 6 to 10 times smaller than the distance between the carbides. The measured Vickers hardnesses H_s (50 gf) of matrices after the testing are reported in Table 1.

X-ray analyses were done in order to verify if structural modifications occur in austenitic white cast iron. To eliminate small composition differences from one sample to another, the X-ray analyses were performed on the same sample: on the worn surface and in the bulk material. For this purpose, a disc was cut from the end of the pin with a low speed diamond saw. One face of the disc corresponded to the worn surface and the other face to the bulk material. The spectrum was obtained after a scanning of Bragg angles at a rate of 1 degree/min. CuK_α radiation was used.

WEAR RESULTS - The corrected mass loss (corresponding to the mean of two measurements) is reported in Figure 3 as a function of the load on the specimen during the test. For all types of cast iron, the wear increases with the load. Austenitic white cast iron (2A) shows the best wear resistance under all load and abrasive hardness conditions. The slopes of the straight lines correspond to the wear rates. For the three types of abrasive employed, the wear rate of austenitic cast iron is slightly lower than the wear rate of the other cast irons. The behaviors of the martensitic cast irons (1A and 3B) are similar to each other within the experimental error. The increasing order of abrasive wear resistance for the various cast irons is: ferritic (4B), martensitic (1A and 3B) and austenitic (2A) cast irons. However the wear rates, from the least to the most resistant cast iron, are of the same order of magnitude.

The wear resistance, defined as the inverse of mass loss for an abrasion distance of 6 m, is plotted in Figure 4 as a function of surface matrix hardness H_s. The harder is the matrix, the better is its wear resistance. There is also an effect of the type of abrasive. The hardness of the

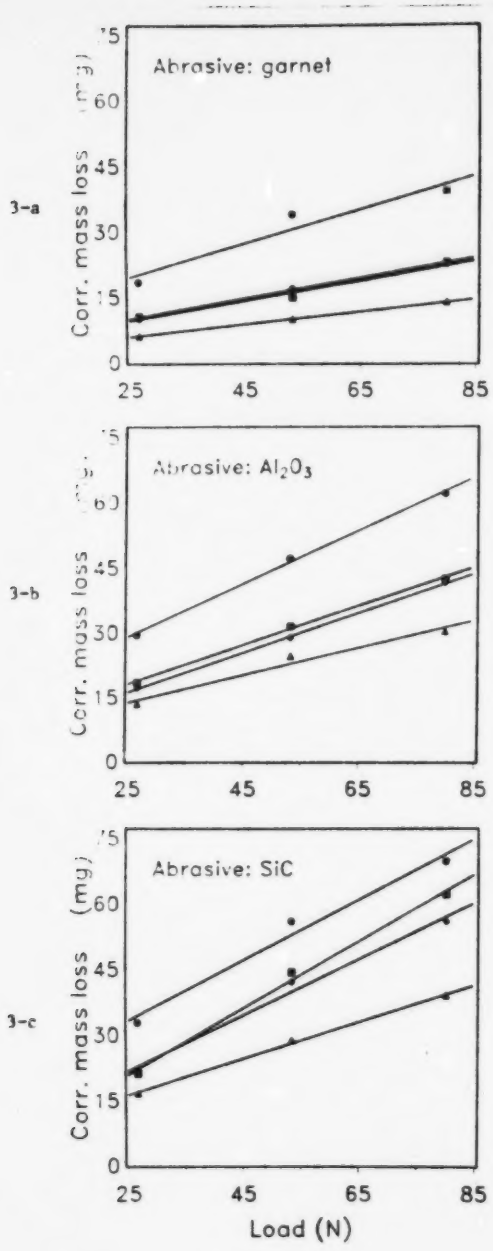


Fig. 3 - Corrected mass loss versus normal load on samples. Comparison of each cast iron for abrasionon a) garnet, b) alumina and c) silicon carbide abrasive paper.

material undergoing wear testing is an important parameter as is also the relative hardness of the material compared to the hardness of abrasive. The values of hardness for the abrasives employed were taken from ref. [14,15]. These are: 1350 HV for the garnet, 2000 HV for the alumina and 2600 HV for the silicon carbide. The wear resistance as a function of the ratio of the matrix hardness H_s to the abrasive hardness is plotted in Figure 5. For a given load, the wear resistance increases as the ratio H_s/H_a increases. Except for the level of wear resistance, the shapes of the curves of Figure 5 are similar from one load to another. In all cases, the surface matrix hardness is significantly lower than the abrasive hardness.

SEM OBSERVATIONS - The wear mechanisms identified on the worn surfaces are microcutting and ploughing. The ploughing mechanism is observed from the occurrence of plastically deformed lips on the sides of wear grooves. The intense stress at the tip of abrasive particles results in plastic strain in the surface layer even in the case of a hard martensite matrix, as shown in Figure 6. Typical worn surfaces of each cast iron for the same load and type of abrasive are illustrated in Figure 7. When looking at these micrographs, it is possible to distinguish the ferritic cast iron from the martensitic or austenitic cast irons by observing the differences in groove depths and groove lip dimensions. Austenitic and martensitic cast irons have almost the same worn surface characteristics.

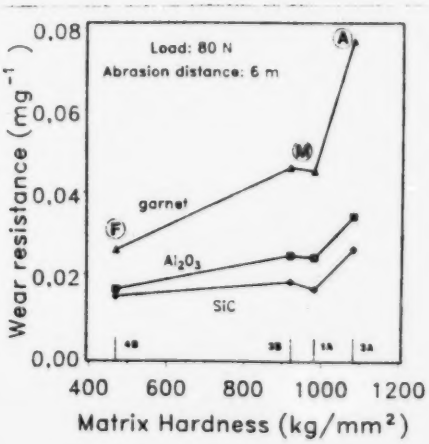


Fig. 4 - Wear resistance versus matrix hardness measured after the test.
A: austenitic, M: martensitic, F: ferritic.

Before the observations under the scanning electron microscope, some samples were lightly etched to observe the wear

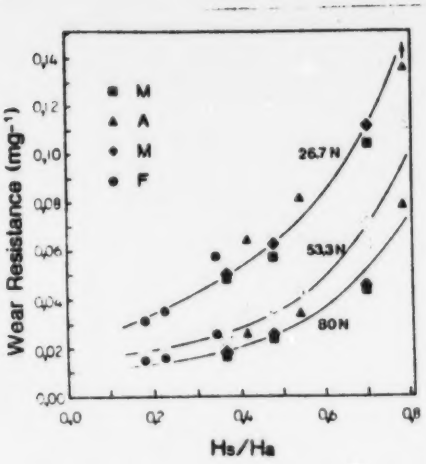


Fig. 5 - Wear resistance versus the ratio of the matrix hardness to the abrasive hardness.

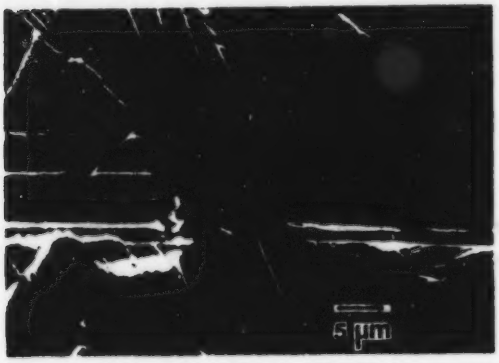
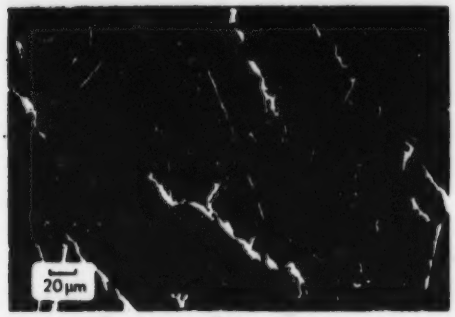


Fig. 6 - Important plastic deformation occurs at the intersection of two wear grooves. Cast iron 1A tested under a load of 80 N with SiC abrasive paper.

mechanism of eutectic carbides and the behavior of the matrix-carbide interface. Figure 8 shows that there is no evidence of discontinuity of wear grooves at the matrix-carbide interface. The grooves in the carbides look smooth and no evidence of plastic deformation occurs such as in the matrix. Some samples were cut perpendicularly to the test surface in order to observe the deformation of material under the worn surface. Figure 9-a illustrates that the carbides are broken to a depth up to 15 m for the ferritic cast iron. Moreover, this figure shows decohesion between the carbide and the matrix. This is usually an indication of severe plastic deformation of the matrix which would be the most likely cause of the breakage of carbides. This also occurs to a lesser



7-a

7-b

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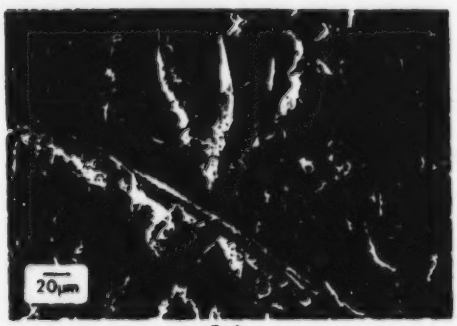


7-d

Fig. 7 - Typical worn surfaces of cast iron a) 1A, b) 3B, c) 2A and d) 4B tested under a normal load of 53.3 N with SiC abrasive paper.

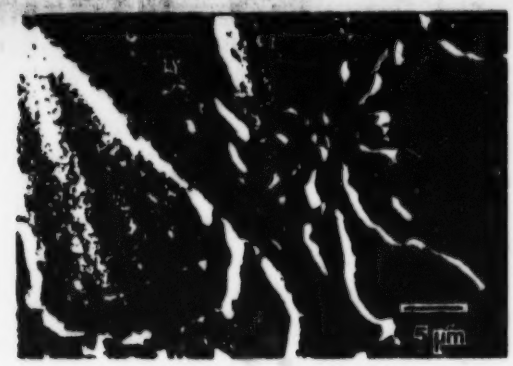


Fig. 8 - Abrasion groove through eutectic carbides on cast iron 3B tested for a load of 80 N with garnet abrasive paper.

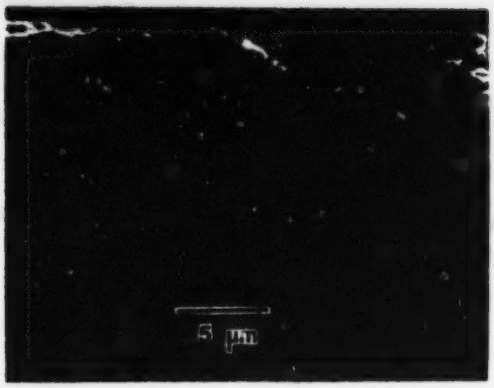
extent in the austenitic cast iron because plastic deformation is sufficiently high at the surface. The hardness of the austenite matrix limits the depth of the damage (Fig. 9-b). Carbide fracture was rarely observed for the martensitic cast iron. Instead of this, the bending of eutectic carbides toward the direction of abrasive movement (Fig. 9-c) is associated with a good cohesion between the carbides and the matrix.

X-RAY ANALYSIS - The spectra obtained by X-ray diffraction of the bulk austenitic cast iron and of the worn surface of the corresponding material are shown in Figure 10. The peak intensity of the M_7C_3 phase is the same in the two spectra because the amount of eutectic carbide does not change between the two opposite faces of the sample chosen (one face corresponds to the worn surface and the other to the bulk material). One can also observe an increase of α martensite on the worn surface associated with a decrease of austenite (γ). The behavior is the same for the other minor peaks which are not shown in this figure.

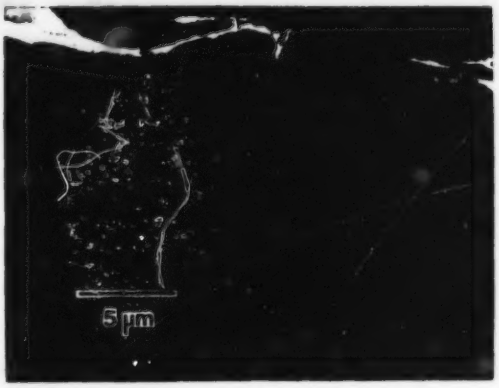
The worn surface also contains andradite $(Ca_3Fe_2(SiO_4)_3)$ which is a common garnet constituent giving the brownish-reddish color to the abrasive grits. This indicates that in spite of the ultrasonic cleaning, the abrasive debris remain embedded.

DISCUSSION

The material loss due to abrasive wear is related to the penetration depth of abrasive grit. The relation between the wear and the load (Fig. 3) exists because the penetration depth increases with the load. For this reason, there is a good correlation between the wear resistance and hardness of pure materials [16]. The presence of a second phase modifies the wear behavior of materials generally in a different way than the one predicted by the linear rule of mixtures [5].



9-a



9-b

9-c

Fig. 9 - Views perpendicular to the worn surface of samples a) 4B, b) 2A and c) 3B tested under a normal load of 80 N with Al_2O_3 abrasive paper.

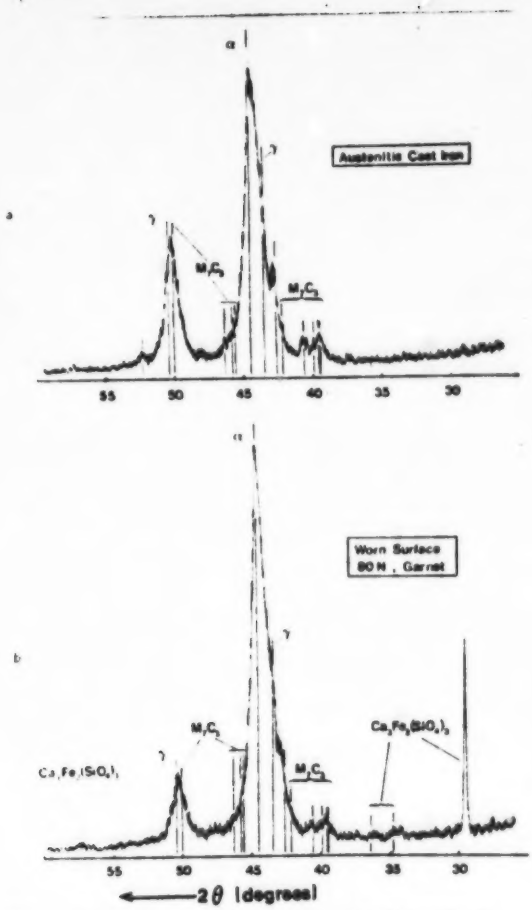


Fig. 10 - X-ray diffraction spectra of an austenitic cast iron a) in the bulk material and b) on the worn surface.

The wear resistance of a material such as cast iron can be deduced by observing separately the resistance of the matrix, the eutectic carbides and the behavior of the matrix-carbide interface formed by the intimate contact between the two phases.

WEAR OF THE MATRICES - The wear of white cast iron with a martensite matrix occurs by microcutting and ploughing. During the abrasion test, extensive deformation within the surface layer produces heat [17,18] that tends to improve the toughness and the ductility of the brittle martensite. The depth of this surface tempering corresponds to the thickness of the plastically deformed layer [18]. This thickness depends on the type of abrasive and the bulk hardness of the material. The hard region under the surface layer limits the penetration of abrasive particles and only a small fraction of eutectic carbides are abraded during the test.

For the austenitic cast irons, the higher wear resistance is associated with the high hardness of the surface layer. The micrograph of the worn surface (Fig. 7) shows a very small amount of lip formation beside grooves. In most cases, the lips are totally absent as compared to the martensitic or ferritic cast irons. The fact that the surface hardness of the matrix at the end of the test is much higher than the bulk hardness indicates that strong work hardening occurs within the surface layer. The strain-induced martensitic transformation observed (Fig. 10) also contributes to the hardness increase of the austenite matrix [11]. Pearce [11] also has observed a hardness of the work-hardened austenite matrix of early 950 HV. On the other hand, Samuels [17] mentions that it is difficult to observe evidence of martensitic transformation in the surface layer. The intrinsic ductility of the austenite matrix tends to favor the ploughing mechanism which is known not to produce material losses [19]. The method employed to measure the surface hardness seems to be good because the curves in Figure 2 are similar for the three loads suggesting that the depth of the penetration marks is contained entirely in the work hardened layer. Moreover it indicates that the wear mechanisms do not vary in the range of loads selected. The austenite matrix is more wear resistant than the martensite matrix, in this study, because the higher surface hardness of the austenite restricts penetration by the abrasive grit to a shallower depth.

The low hardness of the ferrite matrix is mostly responsible for the higher wear losses because the penetration depth is higher. During the microcutting and ploughing of this soft matrix, another wear mechanism is involved. The micrograph in Figure 7-d illustrates the lip and groove tearing of ferritic cast iron. The microcracks created by this mechanism facilitate material removal during the subsequent passage of abrasive particles. The low hardness of ferritic cast iron after testing, as can be seen in Table 1, indicates that work hardening is not significant.

WEAR OF EUTECTIC CARBIDES - The eutectic carbides in white cast irons play an important role. The hardness of these carbides is about 1300-1800 HV [8,15] and lies between the hardnesses of garnet and alumina. Even though garnet is slightly softer than M_7C_3 carbides, grooves in carbides are formed indicating that the angularity of abrasive particles is a part of the wear system that also has to be taken into consideration. The plastic deformation of eutectic carbides already has been observed [11]. The ratio of M_7C_3 carbide hardness to garnet hardness gives values of 0.95 to 1.32 which are slightly greater than the value of 0.8 defined by Richardson [20] as the limit of ability of abrasive particles to produce

grooves on carbides. The high stress at the tip of an abrasive particle can induce plastic deformation even in a brittle material. From our observations, the abrasive particles cut M_7C_3 carbides at the same rate as matrix material. This is deduced from the absence of protruding carbides on the surface (Fig. 8) and the constant size of the grooves from the matrix to the bigger carbides (5-20 μm).

MATRIX-CARBIDE INTERFACES - The wear resistance of white cast irons is strongly influenced not only by the matrix and carbide phases but also by the behavior of the interface common to the two phases [5]. The different ratios of the hardness of the matrix to the hardness of the eutectic carbides for the different cast irons tested result in stress concentration in certain regions around the carbides. The much smaller ratio for the ferritic cast iron brings a deformation mismatch between the ferrite matrix and the eutectic carbides; decohesion follows [14] (Fig. 9-a). The eutectic carbide structure is then broken under the surface with the result that subsequent removal of material becomes easier. The tearing in the grooves (Fig. 7-d) can be attributed to the matrix-carbide decohesion. For the martensitic cast iron, the hardness of the matrix is sufficiently hard not to undergo large plastic deformation. The matrix then can support the carbides in order to limit their fracture. The fact that no decohesion appears around the bent eutectic carbides suggests that the deformation mismatch between the martensite matrix and the carbide is small enough to result in homogeneous deformation of both phases at the worn surface. The behavior of the austenitic cast iron falls between those of martensitic and ferritic cast irons. The plastic deformation at the surface causing work hardening brings limited breakage of carbide because the penetration depth of the abrasive is small. Moreover, because the hardness of the matrix is sufficiently high, no decohesion at the matrix-carbide interface was observed. However the bending of carbides, as it occurs for the martensitic cast irons, was not observed either.

Generally, to have a good abrasive wear resistance, the cast iron should have the ability to undergo plastic deformation of both phases to absorb the energy of abrasive particles.

CONCLUSIONS

The following conclusions are based on the abrasion test results and on the observations of worn samples with the scanning electron microscope:

- For all the cast irons tested, the occurrence of microcutting and ploughing as wear mechanisms has been observed. The proportion of ploughing increases with the ductility of the matrix. Also, because of ductility, the groove depth is well correlated with abrasive wear losses. For the ferrite matrix tearing in the grooves results in surface deterioration which increases the mass loss compared to other matrix microstructures for a given experimental condition.
- Decohesion at the interface between the ferrite matrix and the carbides and the related carbide fracture under the worn surface result in high wear rate compared to other matrix microstructures investigated.
- The austenite matrix shows better wear resistance than the martensite matrix in spite of the fact that the initial hardness of the austenite matrix was lower than the hardness of the martensite matrix. The strong work hardening of the austenite matrix is responsible for the good wear resistance.
- Because the microstructural features are of the same order of magnitude as the abrasion grooves, the wear rates of the eutectic carbides and the matrix are the same for a given cast iron microstructure.

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